The Distribution of Gas and Gas Hydrate at Natural Seeps Inferred from Seismic Data

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Abstract- The Naval Research Laboratory has conducted detailed seismic and acoustic investigations at natural methane hydrate seep sites at several locations worldwide. The seismic expressions of these features exhibit significant differences, such as bathymetric expression (mounds, pockmarks, pavements) and the positions of the faults that are likely acting as methane-supplying conduits. Similarities include the way in which the base of gas-hydrate stability, a pressure and temperature boundary is perturbed upward by the warm, upward advecting fluids that supply the seep. In all areas observed, massive, sediment-displacing deposits of gas hydrate on or within about one meter of the seafloor are consistent with a localized conduit supplying the methane, but also brings heat, thereby thinning the zone in which hydrates are stable. Although massive gas hydrates on the seafloor are one of the most visible types of gas hydrate accumulation, they appear to be very localized.

I. Introduction

Gas hydrate is an ice-like assemblage of gas and water that exists only under high pressure and/or low temperature [1]. Most of the gas in naturally occurring gas hydrates is methane, with other gases present in only trace amounts. The phase boundary between the pressure-temperature (PT) regime where methane is stable as either gas or gas hydrate is sharp – neither can exist in the other's PT regime. Because the earth warms with depth below the seafloor, the phase boundary, the base of gas hydrate stability (BGHS) marks the depth below which methane is stable as a gas, and above which methane is stable as methane hydrate. The exact depth of the BGHS depends on the pressure, i.e. water depth, and geothermal gradient, but because it is sensitive to temperature, it tends to parallel the geotherms, and therefore mimics seafloor bathymetry. Seismic data are extremely sensitive to even small gas accumulations, so if gas accumulates at the BGHS it can be easily detected in reflection seismic sections as a bottom-simulating reflector (BSR, lower black dashed line in Figure 1) that is independent of conventional sedimentary boundaries [2]. With BSRs, seismic reflectivity can be used to remotely infer a pressure-temperature boundary through the sediment, thereby constraining the thermal regime of the sediments [3].

Sediment compaction due to forces that are vertical, horizontal or both, causes dewatering of the sediment column and the expulsion of pore fluids upward to the sediment surface, usually the seafloor [4], but also on land (Figure 1). The expelled pore waters are typically enriched in methane and other solutes, and depending on their source depth can be significantly warmer than the surrounding seafloor sediments. In the vicinity of seeps, localized fluid flux brings heat that perturbs the BHGS upward, allowing free gas to exist at a sediment depth that would otherwise lie within the regional gas hydrate stability zone. The upward advecting warm fluids perturb this boundary upwards and create a bell-shaped base of hydrate stability. The perturbation may manifest in seismic profiles as a gas chimney, within which reflections are obscured or reduced in amplitude (Figure 2), or, if the gas is distributed at the BGHS, a bell shaped reflection is seen in seismic data [5]. The exact shape (width) of the bell can be modeled and used to constrain various aspects of the heat and fluid flux.

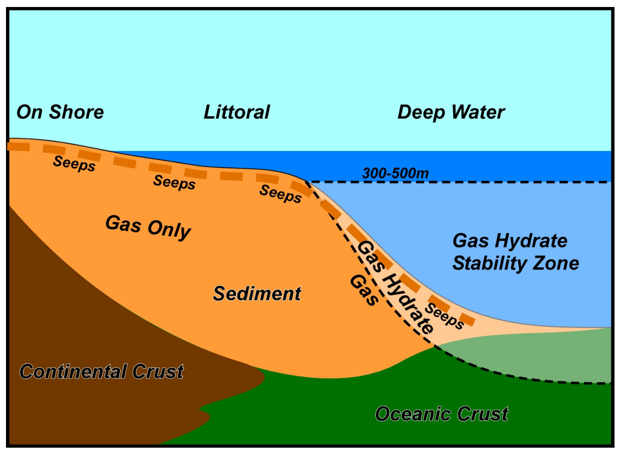

Figure 1. Although seeps occur wherever water is being expelled upward through sediment (even onshore), marine gas hydrates can only occur in deep water (shaded area), and where methane concentrations exceed saturation. On passive margins the gas hydrates are typically found on the continental slopes and rises.

II. Observations at Selected Field Sites

Researchers at NRL have observed gas hydrates at a variety of depths on both passive and active continental margins. Figure 2 shows an example of a seismic section acquired with NRLs (Deep-Towed Acoustics/Geophysicis System) [6] on the Cascadia Margin off Vancouver Island. The data were acquired in a field of seeps manifesting in Figure 2 as gas chimneys (black arrows in Figure 2), some of which are associated with seafloor expressions such as pockmarks or pavements [3]. In this area a strong regional BSR is clearly visible in lower frequency surface towed data, but is visible in Figure 2 acquired with higher frequency data

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only very faintly, if at all (gray arrows). The frequency dependence of the reflectivity is caused by the how the gas is distributed in the sediments relative to the sonic source wavelength [3,5]. A gas accumulation boundary that is sharp compared to a wavelength causes increased coherent reflectivity, while more dispersed gas accumulations (relative to the wavelength) scatter the reflected energy incoherently.

We have also observed hydrate related Gas chimneys, (also called "wipe-outs" because they obscure stratal reflections), offshore Chile [7], the Gulf of Mexico [5], the Blake Ridge [8], the Hikurangi Margin off New Zealand [9], and the Nankai Trough off Japan. The Nankai, Hikurangi, Cascadia, and Chile margins are all convergent margins. The driving force for upward fluid advection is lateral compression of sediments as they are accreted on to the margin. The Blake Ridge Diapir, and Gulf of Mexico sites exist in passive margin settings. The driving force for vertically advecting fluids on passive margins is sediment compaction from gravity.

At many of these sites, bright discontinuous reflections interpreted as shallow gas are exhibited meters to tens of meters below the seafloor, well within the regional gas hydrate stability zone, and at a seafloor location where solid methane hydrates were recovered with piston coring or other direct sampling. However, not all sites exhibit a bell-shaped amplitude reduction, or smooth reflection.

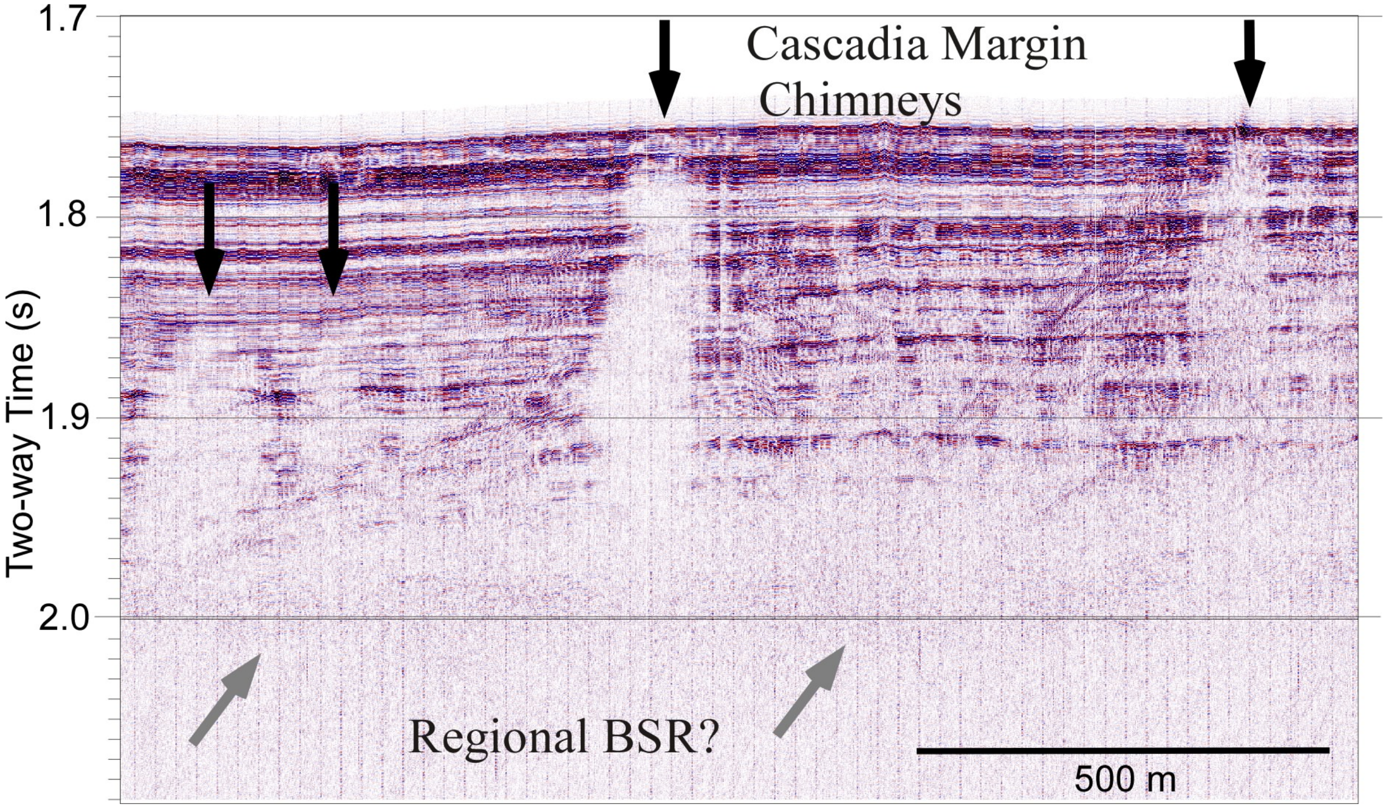

Figure 2. DTAGS profile from the Cascadia Margin off Vancouver Island Canada shows small gas chimneys (black arrows) of varying opacity, only some of which reach the seafloor. At the depth of the expected base of gas hydrate stability the (very incoherent) reflections exhibit slightly greater amplitude (gray arrows).

III. INTERPRETATION

Figure 3 shows line drawings made from four seismic profiles, each observed at a hydrate related fluid expulsion site, all plotted at the same vertical and lateral scale, and plotted with no vertical exaggeration. In each area the blue line indicates the seafloor, and the green line indicates the interpreted top of gas (assumed to be the BGHS). The red line indicates the regional, or expected BGHS based on a laterally constant geothermal gradient. The overall size and shape of the perturbations is similar, ranging from one hundred to a few hundred meters, and broader at the base than at the top. Gas hydrates are more stable at the seafloor than at depth so a given thermal perturbation has a greater affect at depth than at the seafloor. The Vancouver Island and Gulf of Mexico sites exhibit more characteristically bell shaped curves, suggesting that at these sites the conduits responsible for heating the sediments are more nearly vertical.

All methane hydrate related seeps sites observed are consisted with a model of heat and fluid expulsion depicted in the conceptual diagram shown in Figure 4. Natural dewatering, regardless of the cause, forces warm pore water upward along conduits, probably pre-existing weakness in the sediment such as faults. These warm waters are rich in many solutes, including methane. If and when the concentration of the solute exceeds saturation, a precipitate forms. In the case the case of gas, the methane comes out of solution as a gas below the hydrate stability zone, and as a gas hydrate when within the stability zone. In many cases the stability zone can be perturbed all the way to (or near) the seafloor, and may be associated with a pockmark or mound. Individual pathways may become clogged and subsequently bypassed using newer conduits.

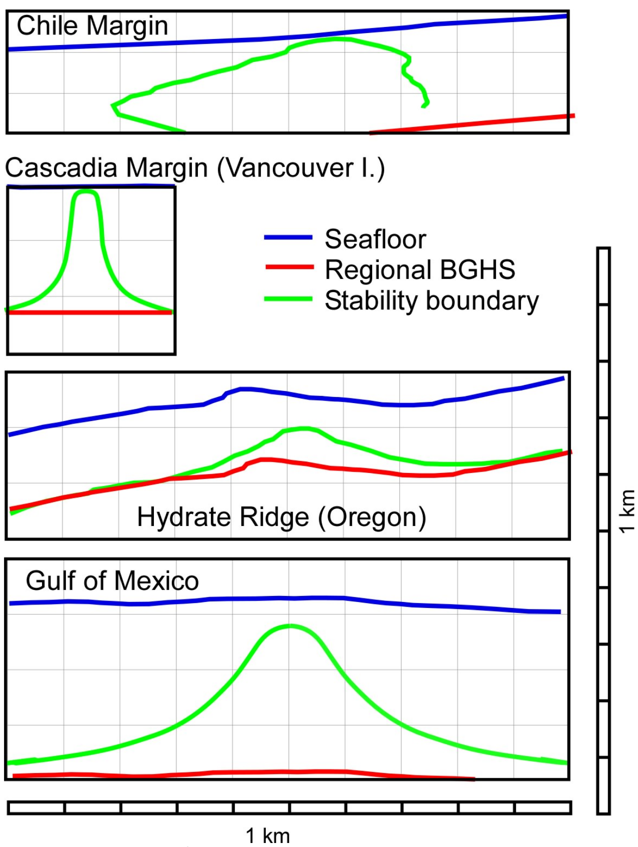

Figure 3. The shapes of stability zone perturbations are varied but typically exhibit road base and a narrow top, with the central peak corresponding to the conduit responsible for the heat transport.

IV. Conclusions

High resolution and deep-towed seismic profiling can be used to accurately determine the geometry of potential fluid conduits in sediments. The sensitivity of the seismic and acoustic measurements to gas allows us in many areas to delineate the exact position of the methane hydrate phase boundary. In all areas observed, massive, sediment-displacing deposits of gas hydrate on or within about one meter of the seafloor are consistent with a model in which a conduit supplies the methane, but also brings heat, thereby thinning the zone in which hydrates are stable. In addition to this vertical localization, the conduit itself is also responsible for the significant lateral localization of the flux. Only a few meters away from the conduits, methane and flux at the seafloor is at background values, typically below methane saturation so no methane hydrates are formed. Thus, although massive seafloor gas hydrates are one of the most visible types of gas hydrate accumulation, and most readily sampled, they are likely very localized.

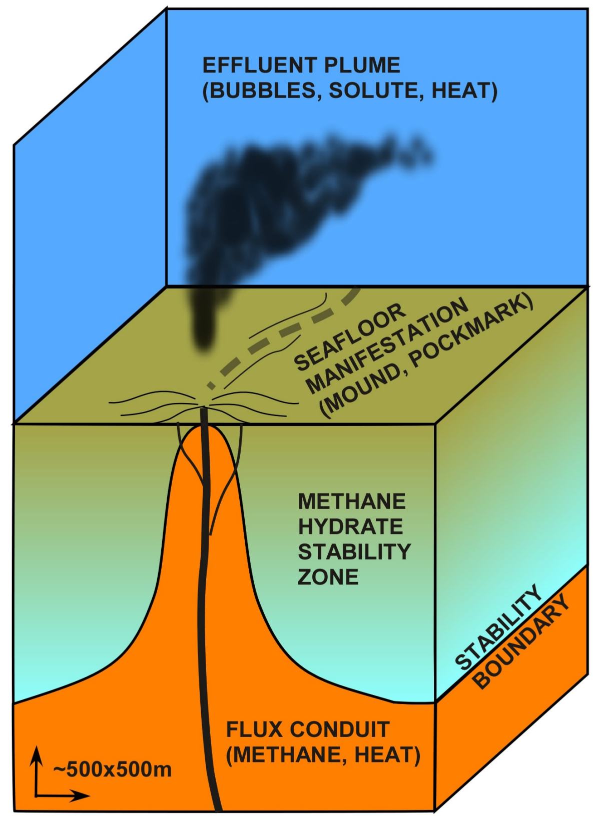

Figure 4. Most observations are consistent with a model of heat and methane flux through conduits, probably along faults, that bring fluids enriched in methane, but also carrying heat that perturbs the base of gas hydrate stability upward.

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